Jet Propulsion Laboratory
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# A 6U HYBRID PROPULSION MODULE FOR CUBESATS

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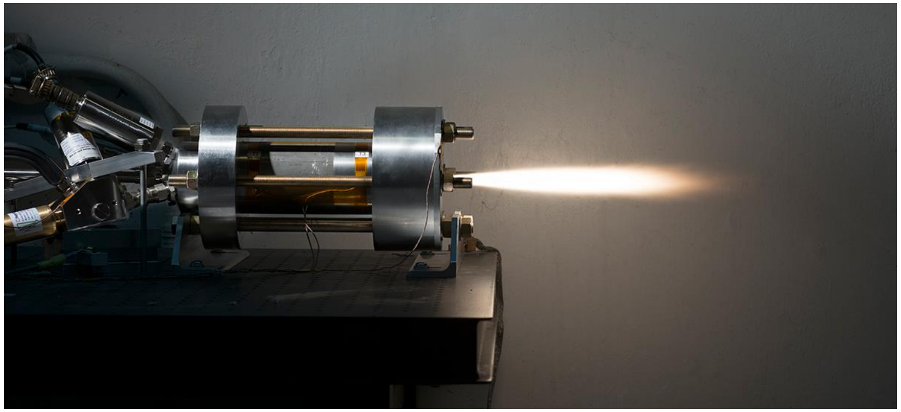


# Agenda

- Introduction
- 6U Propulsion Design
- Test Setup
- Results
- Future Work
- Conclusion

# Introduction

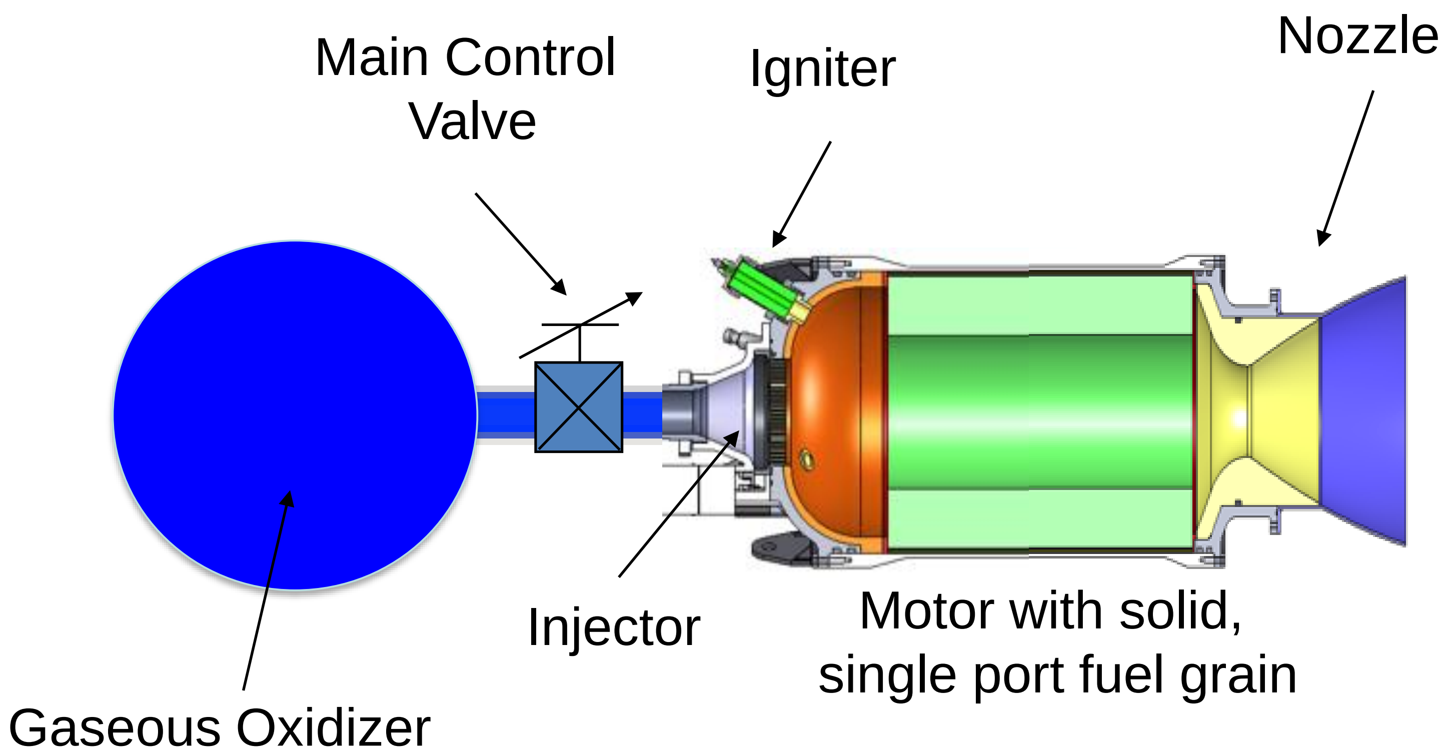
- A 6U propulsion system is proposed to enable substantial propulsive capability for up to 25 kg of wet mass
  - This study is the result of a JPL internally funded research and technology development program.
  - 6U is defined as 36.6 cm by 23.9 cm by 11.6 cm

- Potential applications of this small-scale hybrid system include orbit insertion, change of orbit, breaking burns, flybys, and deorbit burns.
  - The hybrid is especially advantageous for these larger/longer burns because of its increased thrust compared to typical monopropellant systems.

- Hybrid fuel regression rate for combustion of PMMA/Gox was found to be different than literature.

$$\dot{r} = a_o G_{ox}^n$$

# What is a hybrid?



# 6U Propulsion Design

- Payload (non-prop dry mass) and ΔV are presented

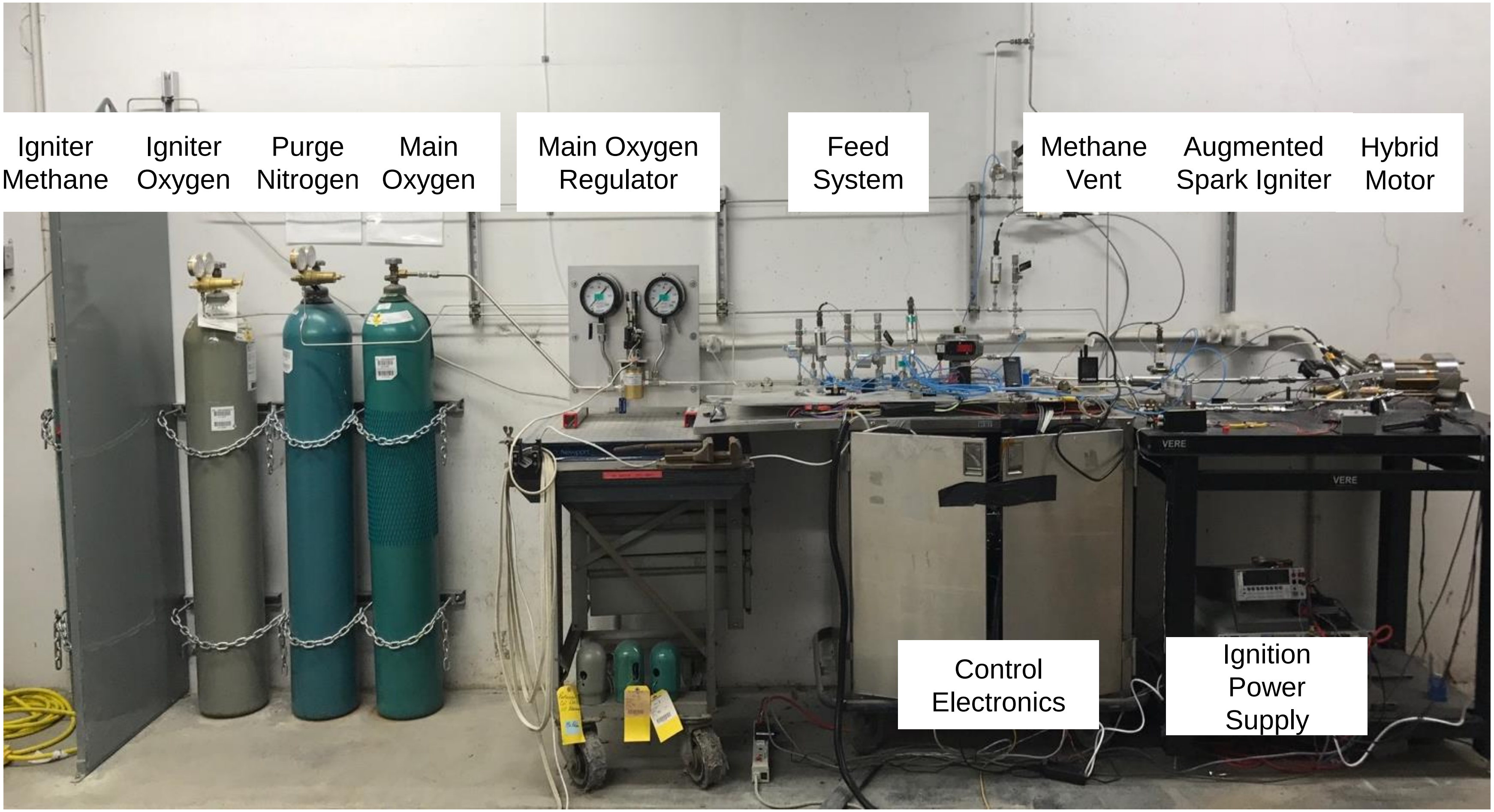
| Total Spacecraft Mass (Wet) | 15 kg | 20 kg | 25 kg |
|---|---|---|---|
| **Payload (Available Non-prop Mass)** | 3.4 kg | 8.35 kg | 13.36 kg |
| **ΔV** | 540 m/s | 400 m/s | 315 m/s |

- Propulsion system dry mass of 8.33 kg
  - Components: 5.67 kg of components (including margin)
  - Primary structure:15% of the spacecraft wet mass
  - Secondary structure, thermal and cabling: 25% of wet mass
  - AIAA S-120 margins are applied to all estimated masses
  - The propulsion system is self-contained except for the avionics and battery which are shared with the main system to reduce mass.

# 6U Propulsion Design

- A single motor with two high pressure oxidizer tanks (10,000 psi)
  - This is considered to be low risk since oxygen containment and handling at 10ksi has flight heritage. An example is the spare oxygen tanks Apollo astronauts carried for emergencies
- Oxygen cold gas systems
  - TVC: four 1.1 N thrusters (2% of useful propellant)
  - RCS: eight 0.05 N thrusters (158 grams)
- Assumes a 28 V power supply. Operation at decreased voltage is possible for a small mass penalty

# Ambient pressure test setup



# Ambient pressure test setup

- Approximately 30 tests with this propellant combination have been carried out from 1 to 95 s in duration.
- Objectives:
  - Regression rate coefficients
  - Multiple restart capability
  - Fuel utilization
  - High performance

# Regression Rate

- JPL experimentally derived regression rate coefficients found to be different than previously published values.
  - Fuel regression is faster, enables a single motor to fit within the CubeSat form factor.
  - Chemical composition of PMMA can vary $(C_5O_2H_8)_n$.
    - Tests carried out for PMMA from two different vendors

$$\dot{r} = a_o G_{ox}^{n}$$

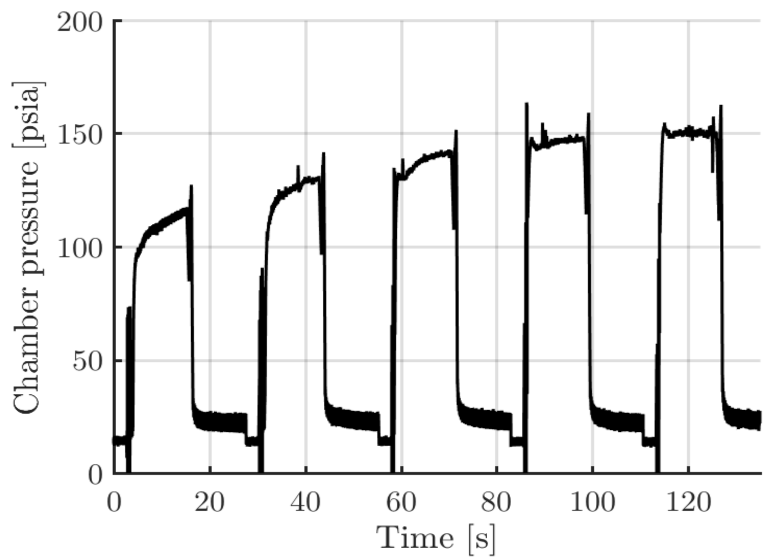
| | $a_0$ | n |
|---|---|---|
| **JPL** | $9.40 \times 10^{-5}$ | n = 0.34 |
| **Zilliac and Karabeyoglu**[1] | $2.11 \times 10^{-5}$ | n = 0.615 |

[1] Zilliac, G. and Karabeyoglu, M., ***Hybrid Rocket Fuel Regression Rate Data and Modeling,*** 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Joint Propulsion Conferences, American Institute of Aeronautics and Astronautics, July 2006.

# Multiple Starts

- Five ignitions have been demonstrated autonomously on a single motor. This has now been confirmed through two separate tests
  - Each start is stable and repeatable
  - This is not a limit, but the current goal for demonstration

JPL Hybrid Facility: Test 69

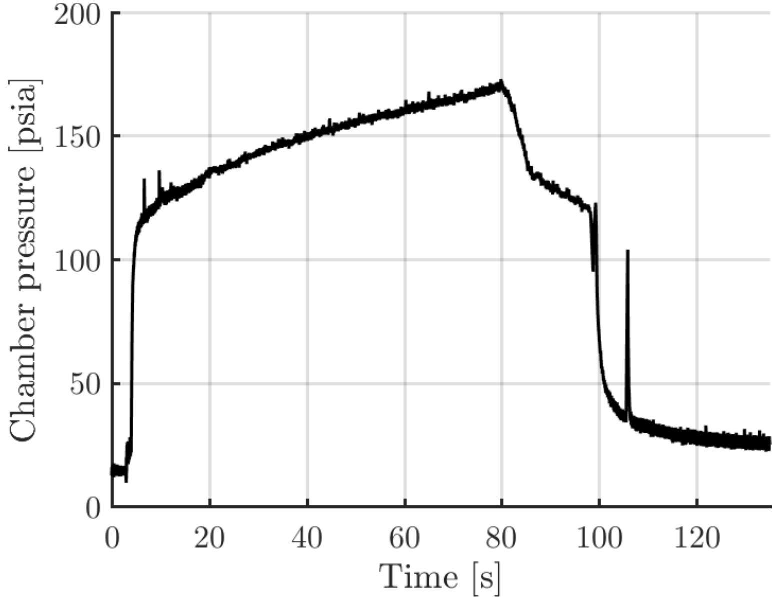


# Multiple Starts (Test 74)

# Fuel Utilization

- Two near full duration tests have been completed to date.
  - The first was 95 s and achieved 94.3% fuel utilization
  - A second test of 95 seconds, spilt up between 5 burns, achieved 97.5% fuel utilization.
- All fuel remaining was at the front of the combustion chamber
- The injector was modified between the two tests in order to allow the oxidizer to more completely mix with the fuel. Further refinement is necessary.

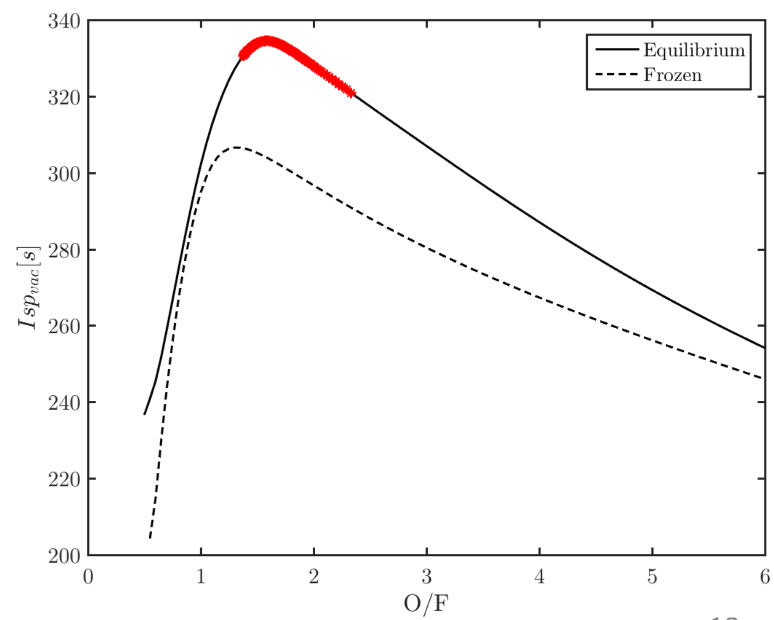
JPL Hybrid Facility: Test 73




# Specific Impulse

- Design Isp: 311 s
  - Requires an efficiency of 93%, (equilibrium combustion and includes O/F shift loss of ~1%)
  - Ideal vacuum Isp is 334.5 s (O/F 1.6)
  - O/F shift is shown at the right. The mean ideal Isp during the burn is 332.1 s
- Testing at JPL has demonstrated combustion efficiencies in the range of 80-95%
  - Validated the design assumption

O/F Shift



# Comparison to the State of the Art

| | Hybrid (PMMA/GOx) | State of the Art: Monopropellant | | |
|---|---|---|---|---|
| | | Hydrazine | HAN 10% water (AF-M315) | ADN (LMP-103S) |
| Available Non-Propulsion Mass/ Payload | 16.67 | | | |
| Main Advantage | High Isp/Thrust | TRL | Higher Density than hydrazine | |
| Isp (Performance) | 311 s | 227 s | 213 s | 233 s |
| Thrust [N] | 50 | 21 | 20 | 20 |
| Delta V for 12U, 25 kg | 315 | 148 | 61 | 89 |
| Prop System % Volume | 67.8% of 6U | 71.5% of 6U | 74.8% of 6U | 66.1% of 6U |
| Cold Survival Temperature [C] (5 C margin) | ~-150 | 8 | -75 | -85* |
| Toxicity/Issues | Nontoxic | Toxic | Acidic, titanium components only | Similar to Ammonia, Precipitate is 1.4 explosive |
| Single Burn Impulse [Ns] (e.g. 1 hr OI burn) | 5,050 | 2,520 | 4,950 | 2,640 |

# Future Work

- Vacuum testing
  - Raise TRL from 4 to 5(+)
- Subsystem level testing
  - The main oxidizer valve will be tested this year (TRL 5+)
  - Other system level components will be tested in the future, but do not have such a direct impact on the performance of the system.
    - The development of high pressure, miniature, oxygen compatible components will be required.
- Complete system development will take ~2.5 years with adequate funding.
  - The high-pressure components will drive the cost and schedule of this system. However, they also enable the high performance in the small propulsion module

# Conclusions

- A 6U hybrid propulsion module for CubeSats has been presented.

- Depending on the mass of the rest of the system, the propulsion module, taking up 6U and 1/3 of the spacecraft mass, can provide 315 m/s of $\Delta V$.
  - Up to about 540 m/s is possible.
  - This is a substantial improvement over the state of the art.

- Test data confirm the performance of the PMMA/GOx motor as well as the high-level requirements for the system: multiple starts and reasonable fuel utilization.

- The TRL of the propulsion system is currently 4 and is expected to be increased to 5+ by the end of Sept 2018.

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## Questions?

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